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ORIGINAL PAPER

Overview of the application of laser-based techniques in plasma-wall interaction research program at IFPiLM

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Abstract. The purpose of this paper is to give an overview of the progress in the application of the laser-based techniques which has been achieved in the research in the field of plasma-wall interaction (PWI) at the Division of Laser-Produced Plasmas (DLPP), Institute of Plasma Physics and Laser Microfusion (IFPiLM, Warsaw, Poland) since 2005. The evolution of the experimental set-up which started in a simple configuration for the laser ablative co-deposit removal is presented with stress on the milestones which led to subsequent modifications, namely installation of laser induced breakdown spectroscopy (LIBS), fast HR (high resolution) CCDs, pulsed fiber-laser and the common triggering system.

Key words: plasma-wall interaction • plasma spectroscopy • laser induced breakdown spectroscopy (LIBS)

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Introduction

Together with joining the European Union in 2004, Poland has become an EURATOM (European Atomic Energy Community) member which gave the IFPiLM the opportunity to participate in collaborative works in frame of EURATOM-fusion aimed at the development of the thermonuclear power plant which became a priority issue for Europe and all the world [7]. As the immediate area for co-operation, the works on the PWI have been identified especially in the field of the laser-ablative fuel removal and post-mortem, ion diagnostics based investigation of the tokamak components which were plasma treated during the machine operation. This choice was due to the experience of the Division of Laser-Produced Plasma team and the growing significance of the PWI area especially in the context of the material choice for ITER (international thermonuclear experimental reactor) which contained beryllium, tungsten and carbon [1].

Since this early stage, which included mainly the experiments on the co-deposit removal from TEXTOR (Tokamak EXperiment for Technology Oriented Research) limiter samples [8] characterized by means of the ion diagnostics [2], the research has been evolving due to application of various post-mortem analyses

(SEM – scanning electron microscope; TEM – transmission electron microscopy; NRA – nuclear reaction analysis; QMS – quadrupole mass spectrometer, etc.) conducted in collaborating laboratories [5] which together with the ion diagnostics performance have shown the emerging possibilities and necessities of the extension of the types of equipment present in the set-up. As the most glaring examples there can be mentioned: the application of the optical spectroscopy for the removal process monitoring instead of the ion diagnostics due to its underperformance [4], the application of the dust collectors and ultimately real-time dust observation after the realization of the significance of the dust problem [5] and the application of the fiber laser due to the better parameters of the removal process which can be obtained by its means. In the timescale of the research the overall focus has been shifted from the ablative removal of carbon-based co-deposits to operation in the mixed-material environment defined by the ITER demands. It also provided the need for application of mixed-material samples. Real-machine samples with C:W:H(D) layers were acquired from ASDEX (axisymmetric divertor experiment) Upgrade (AUG) [6] and calibrated samples with Al:C:W:H(D) [3] layers with various contaminants from other collaborating institutes. In the research beryllium has been excluded due to unavailability of the dedicated laboratory, but it has been substituted by aluminum considered as its nearest proxy.

Experiments

Besides the vacuum chamber, the component which persisted all the modification in the set-up was the Nd:YAG pulsed laser (EKSPLA) delivering 3.5 ns pulses of up to 0.6 J at 1064 nm with up to 10 Hz repetition rate. The laser was originally used for the ablative removal and further also as an irradiation source for laser induced breakdown spectroscopy measurements and a source of triggering for all the experimental equipment. The optical spectrometer Me5000 with iCCD (intensified charge-coupled device) (iStar) camera was used for the real-time optical spectra observation with a flexibly defined exposition time and delay after the laser pulse. When the necessity of laser-produced dust has been shown obvious, various types of dust collectors have been applied [5] and ultimately the fast HR CCD camera for the real-time observation has been installed. To investigate the possibilities of minimization of dust-production and substrate damage the IPG Co. fiber laser (which could deliver 100 ns, 1 mJ pulses at a repetition rate of 100 kHz which resulted in 100 W of average output power) has been applied and for the investigation of the gaseous atmosphere on the removal process two micro-valves have been attached to the vacuum vessel.

The modifications led to the construction of the set-up presented in Fig. 1. In the figure it can be seen that all the systems have a common triggering system from the pulse generator which is pre-triggered by the Nd:YAG laser.

During a long-term research, various types of the samples for investigation were used as it was briefly described in the introduction section.

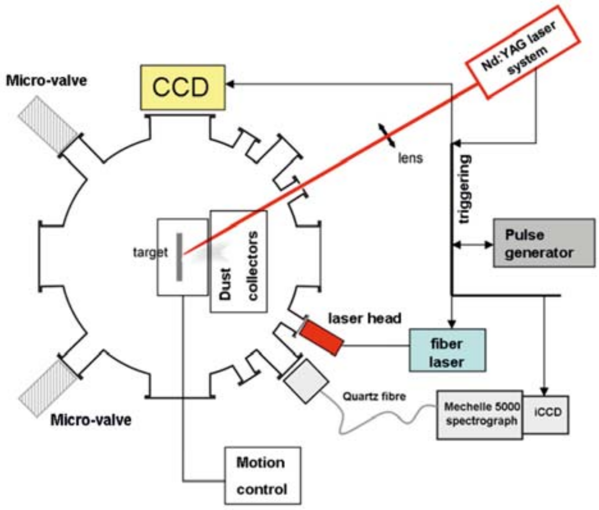

Fig. 1. Experimental set-up for laser-target interaction.

Milestone results

The first phase carried out quickly after the access to the EFDA program was dependent on the immediate confirmation of the possibility and the efficiency of the ablative laser removal of the fuel-containing co-deposit. The confirmation came easily due to the application of the electrostatic ion energy analyzer (IEA) [9] and shown that after the irradiation by a series of 50 laser pulses with power density in the range of 10^9–10^{10} W/cm^2 no deuterium/hydrogen components can persist on the laser treated surface. This was observed for TEXTOR limiter sample. This significant result was first messaged on [2] and here is shown in Fig. 2. To find removed element concentration it is necessary to know a total angular distribution, and the ion concentration is independent of the potential of the IEA.

After successful results also in the application LIBS for this type of carbon-based, a thick TEXTOR-like co--deposit [4], the research has been extended to mixed material samples. As the first samples, the components of AUG divertor from the strike point area were used. The samples were graphite substrates with 4 μm tungsten layers produced by PVD (plasma vapor deposition) and covered with submicron co-deposit layers of

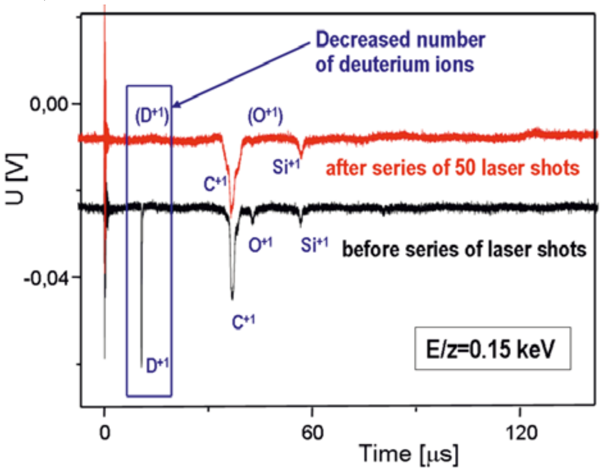

Fig. 2. Decrease in the number of deuterium ions after a series of 50 laser pulses.

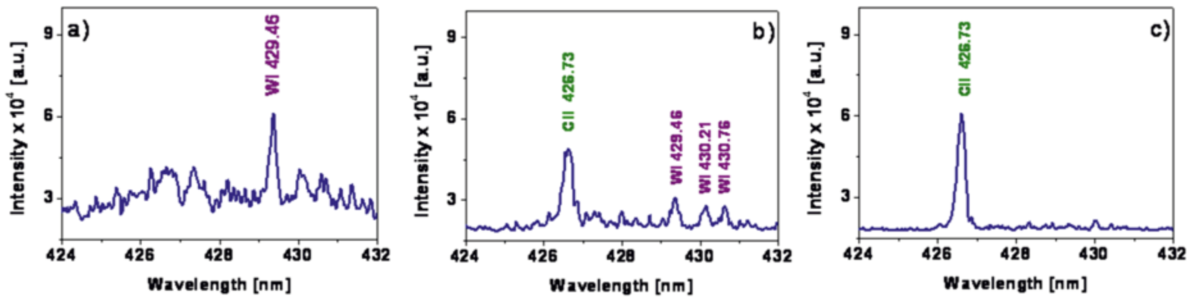

Fig. 3. The spectra obtained for the AUG sample (graphite substrates with 4 μm tungsten layer). (a) Spectrum after 5 laser pulses – the surface layer; (b) spectrum after 25 laser pulses – the boundary of the carbon and tungsten layer and (c) spectrum after 55 laser pulses – graphite substrate.

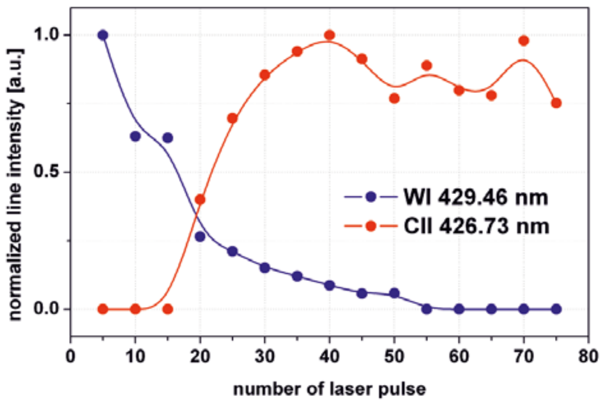

Fig. 4. Spectroscopy-based depth profile of an AUG sample for 10 GW/cm^2 power density.

C:W:D. The results of the investigation of AUG samples confirmed the presence of fuel particles in a thin film on the samples and allowed for the choice of a narrow wavelength range which was very convenient to track the chemical ratio between components of the sample. Exemplary spectra obtained in different subsequent phases of the removal process for power density of 10 GW/cm^2 are shown in Fig. 3.

Integration of the lines allowed for estimation of the depth profile of the samples. A representative one is given in Fig. 4.

The important issue, which is unavoidable when the laser-ablative method of removal is applied, is dust production. Post-mortem analysis of laser-produced dust is extensively described in [5]. Additionally, to get a better insight in the film break-up processes, the fast HR camera has been installed and gave some especially interesting results for the thick TEXTOR co-deposite. The images of the plasma and dust particles released during and after laser interaction have been recorded for various (0–100 μs) delay (time between the laser pulse and starting the acquisition) and acquisition time (10–100 μs). Basing on the recorded traces, the velocity of dust particles was estimated in the range of 100 m/s in vacuum, and it was decreasing with mass and pressure of the gas when it was applied. Moreover, after the image processing and zooming of the dust traces, the "comet" effect for the high pressure of active gases became apparent which suggested that the dust particles were "burning" during their flight. Sample images of dust taken with acquisition time 10 and 100 μs and with delay 40 μs are shown in Fig. 5.

After the attempts were made to minimize the substrate damage and dust production by the means of the fiber laser, the equipment at the IFPiLM has been enriched with the profilometry stage. The direct application of the method significantly enhanced the experimental procedure and allowed for immediate quantification of the laser damage on the target. Sample

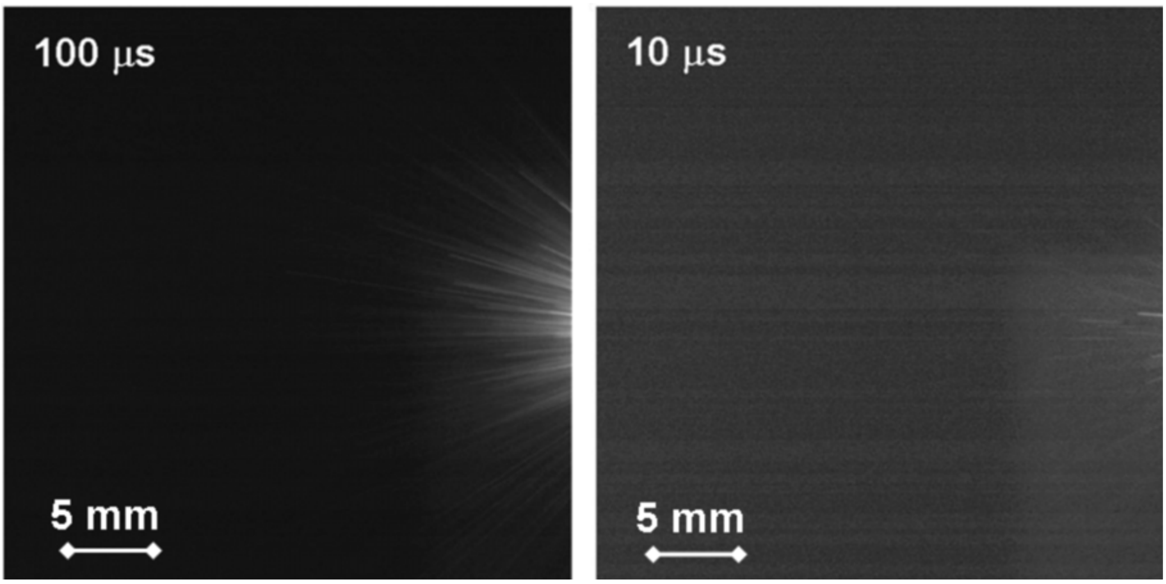

Fig. 5. Exemplary images of dust particles observed 40 μs after laser pulse for different exposition time. The target is located on the right.

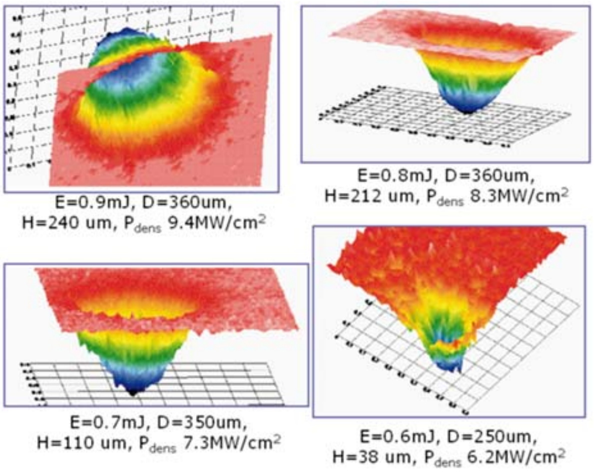

Fig. 6. Exemplary profiles of removal with a fiber laser for graphite samples. D is the diameter of the crater and H is the depth. Fiber-laser was focused on the surface by means of lens with 70 cm of focal length.

3-D (three-dimensional) profiles obtained for the interaction of the fiber laser with graphite samples are presented in Fig. 6. Such profilometry measurements made it possible to assess power-density threshold for removal of the materials of interest which, e.g. for graphite, was estimated at ~ 6 MW/cm^2. Irradiation with slightly lower power density can be considered as capable of removing the deposited layers without substrate damage. It is also worthwhile to mention that no dust was observed in the interaction of the fiber laser beam with any of the target materials.

Conclusions

Several years of research program on the laser-based techniques for PWI interaction at the DLPP, IFPiLM has fruited in a significant progress from a simple, ion-based diagnosed, cleaning system to a multipurpose stage for optimized fuel removal system in vacuum/gaseous conditions with the advanced diagnostics for the wall chemical composition and dust production. The progress was possible not only due to the effort of the IFPiLM team but also thanks to collaboration with the international teams including FZJ (Forschungszentrum Jülich), IPP (Max-Planck-Institut für Plasmaphysik), CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas) and many others.

The further research should be aimed at the quantification of the LIBS measurements in mixed material conditions and optimization of the dustless and substrate-friendly fuel removal by the means of the fiber laser.

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